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## **An Accretion-Induced X-ray Flare in Sgr A\***

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## ABSTRACT

The recent detection of a three-hour X-ray flare from Sgr A\* by *Chandra* provides very strong evidence for a compact emitting region near this supermassive black hole at the Galactic center. Sgr A\*'s mm/sub-mm spectrum and linear polarimetric properties, and its quiescent-state X-ray flux density, are consistent with a model in which low angular momentum gas captured at large radii circularizes to form a hot, magnetized Keplerian flow within tens of Schwarzschild radii of the black hole's event horizon. In Sgr A\*'s quiescent state, the X-ray emission appears to be produced by self-Comptonization (SSC) of the mm/sub-mm synchrotron photons emitted in this region. In this paper, we show that the prominent X-ray flare seen in Sgr A\* may be due to a sudden enhancement of accretion through the circularized flow. Depending on whether the associated response of the anomalous viscosity is to increase or decrease in tandem with this additional injection of mass, the X-ray photons during the outburst may be produced either via thermal bremsstrahlung (if the viscosity decreases), or via SSC (if the viscosity increases). However, the latter predicts a softer X-ray spectrum than was seen by *Chandra*, so it appears that a bremsstrahlung origin for the X-ray outburst is favored. A strong correlation is expected between the mm/sub-mm and X-ray fluxes when the flare X-rays are produced by SSC, while the correlated variability is strongest between the sub-mm/far-IR and X-rays when bremsstrahlung emission is dominant during the flare. In addition, we show that future coordinated multi-wavelength observations planned for the 2002 and 2003 cycles may be able to distinguish between the accretion and jet scenarios.

*Subject headings:* accretion—black hole physics—Galaxy: center—hydrodynamics—magnetic fields—radiation mechanisms: thermal

## 1. Introduction

The unusual radio source Sgr A\* appears to be the radiative manifestation of the “dark” matter concentration at the Galactic center (e.g., Melia & Falcke 2001). Discovered by Balick & Brown in 1974, this object is a bright compact source of cm to mm/sub-mm waves, and appears to anchor the stars swarming around it with velocities in excess of one thousand kilometers per second on orbits with a radius no bigger than about ten light days (Ghez et al. 2000). Despite this compelling evidence that a supermassive black hole accounts for most, if not all, of the inferred  $2.6 \times 10^6 M_\odot$  at the Galactic center, the orbits traced by the stars near Sgr A\* are approximately 30,000 times larger than the predicted size of its event horizon, so alternative explanations cannot yet be ruled out on this basis alone. However, the situation has changed dramatically with the recent *Chandra* detection of an X-ray flare from this source (Baganoff et al. 2001). The ten-minute variability seen during the three-hour event argues for an emitting region no bigger than about 20 Schwarzschild radii (based on light-travel limitations), constraining the volume within which the matter is compressed by a factor 1,500 better than previous studies (Melia 2001). (For Sgr A\*, the Schwarzschild radius  $r_S \equiv 2GM/c^2$  is approximately  $7.7 \times 10^{11}$  cm, or about 1/20 A.U. The gravitational radius  $r_g \equiv r_S/2$  will be used to scale the relevant physical quantities throughout this paper.)

As we shall see below, the characteristics associated with this flare appear to be consistent with a picture in which the dominant emission region, at least at mm/sub-mm and X-ray wavelengths, is associated with a compact Keplerian flow of hot, magnetized gas within  $\sim 12$  gravitational radii of the black hole (Melia et al. 2000; Bromley et al. 2001). This structure may be the inner portion of what forms after the low angular momentum gas (with specific angular momentum  $l \sim 60 cr_g$ ) captured by Sgr A\* circularizes at  $\sim 60 - 100 r_g$  (see, e.g., Coker & Melia 1997). Earlier, we showed that the inner  $\sim 12 r_g$  of such a configuration could not only produce the mm to sub-mm bump in Sgr A\*’s spectrum (Falcke et al. 1998; Melia et al. 2001), but that it could also account for its linear polarization properties (Aitken et al. 2000; Bower et al. 1999; Melia et al. 2000; Bromley et al. 2001). Sgr A\*’s cm radio emission may instead be due to non-thermal synchrotron

processes in the circularization zone, where the flow evolves from quasi-spherical accretion at large radii to a Keplerian structure further in. The *quiescent*-state X-ray emission detected with *Chandra* appears to be produced via synchrotron self-Comptonization (SSC) of the mm/sub-mm photons (Liu & Melia 2001). We note, in this regard, that the latest high-energy observation of Sgr A\* appears to be at odds with the much flatter spectrum predicted by large, two-temperature ADAF disks (Narayan et al. 1995).

The flare lasted about three hours; during that time, the hard band X-ray flux decreased by a factor of five in less than ten minutes, consistent with the viscous time scale for the inner  $6 r_g$  of the infalling gas, where most of the high-energy radiation is produced. The dynamical time scale associated with this region is typically shorter, therefore suggesting that the variability during the outburst might be due to an accretion instability within the circularized flow. This points to a highly dynamic event, for which a detailed numerical simulation is required for proper modeling. Nonetheless, the fact that the relevant time scale for establishing equilibrium (i.e., the viscous time scale) in the inner few gravitational radii is much shorter than the duration of the flare means that we can effectively adopt quasi-steady conditions during the state of enhanced accretion. The initial modeling of such an event is therefore straightforward since the structure of the emitting region depends primarily on this mass accretion rate  $\dot{M}$ . In this *Letter*, we explore a range of possible system configurations that could account for the observed outburst. We demonstrate that the flare can be produced either via thermal bremsstrahlung if the anomalous viscosity decreases with the enhanced  $\dot{M}$ , or via synchrotron self-Comptonization if the anomalous viscosity increases. These scenarios make distinct predictions concerning Sgr A\*'s flare spectrum and the flux density correlations at different wavelengths, which may be tested with future coordinated broadband observations.

## 2. Physics of the Transient Event

Several characteristics associated with the X-ray flare stand out, setting very strict constraints on the nature of this event (Baganoff et al. 2001). First, the flare lasted about three hours and,

near its middle, the 4.5 – 8 keV luminosity dropped abruptly by a factor of 5 in 10 minutes. The 2 – 4.5 keV luminosity followed a similar pattern, though its drop was less sharp, and appeared to lag that of the hard X-rays by a few minutes. Second, the peak of the flaring-state had a luminosity 45 times greater than that of the quiescent-state. This huge enhancement in power suggests that a severe change occurred in the physical properties of the emitting gas, effectively involving the *whole* region. Third, the flare-state spectrum had a spectral index of  $0.3_{-0.6}^{+0.5}$ , which is much harder than that in the quiescent-state (i.e.,  $1.2_{-0.7}^{+0.5}$ ). This contrasts with the prediction of the disc-corona model for AGNs (see, e.g., Ulrich et al. 1997). All these features are quite unique to the X-ray flare in Sgr A\*.

The anomalous viscosity is given as  $\nu \equiv (2/3)W_{r\phi}/\Sigma \Omega$ , where  $\Sigma$  is the column density,  $\Omega$  is the angular velocity, and  $W_{r\phi}$  is the vertically integrated sum of the Maxwell and Reynolds stresses (Balbus et al. 1994). For the problem at hand, the Maxwell stress dominates, and  $W_{r\phi} \approx \beta_\nu \int dz \langle \beta_p P \rangle$  is adequately described by two magnetic parameters in this model:  $\beta_\nu$  is the ratio of the stress to the magnetic field energy density, and  $\beta_p$  is the ratio of magnetic energy density to thermal pressure  $P$ . The radial velocity is given by  $v_r \sim (4\beta_p\beta_\nu/9)(GM/r)^{1/2}$ , assuming the gas temperature attains its virial value. From this, we get the viscous time scale for the gas in the inner few gravitational radii of the disk:  $\tau_v \equiv r_g/v_r \sim 9.6(r/r_g)^{1/2}(0.05/\beta_p\beta_\nu)$  mins. We note that  $\tau_v$  is consistent with the variability time scale ( $\sim 10$  mins) within the flare when  $\beta_p\beta_\nu \sim 0.05$ , which is close to the results produced in detailed MHD simulations (Brandenburg et al. 1995; Hawley et al. 1996), when one takes into account the various approximations made in these calculations, their limited spatial resolution and the differences of the physical conditions between their simulations and the accretion model adopted here.

Under the same conditions, the dynamical time scale for gas flowing within the inner Keplerian region is  $\tau_d = 2\pi r/v_k$ , where  $v_k = (GM/r)^{1/2}$  is the azimuthal velocity at radius  $r$ . Its scaled value  $\tau_d \approx 1.3(r/r_g)^{3/2}$  mins suggests that a non-equilibrium process may be responsible for initiating the injection or depletion of matter through the inner orbits, which then results in an overall fluctuation on a viscous time scale as the disk readjusts. As is well known by now (see,

e.g., Melia et al. 1992), most of the flux from Sgr A\* at a given frequency is produced by gas in a relatively narrow range of radii (with the highest energy radiation being produced in the most compact regions). Thus, whereas the duration of a fluctuation probably corresponds to the time required for viscosity to re-establish equilibrium, the overall extent of the flare may have been attributable to certain characteristics of the infalling plasma (perhaps its spatial extent, or its clumping profile). There are several possible non-equilibrium processes that could have started the dip near the middle of the burst, including a dynamo-induced magnetization of the orbiting plasma. This can happen over one orbital period, i.e.,  $\tau_d$  (see, e.g., Balbus et al. 1994; Melia, Liu, & Coker 2001). This could, among other things, result in a rapid, though transient, increase in the anomalous viscosity, followed by a rapid draining of the inner disk. Other mechanisms include the intriguing possibility that the infalling plasma may be comprised of clumps with a variety of specific angular momenta, so that the material falling in at later times effectively cancels (or reverses) the angular momentum of the material already in orbit about the black hole. This too can lead to a temporary thinning of the inner disk. Unfortunately the photon statistics during the flare were not of sufficient quality for the spectrum to be determined as a function of time; only data associated with the integrated flux are available, so spectral information that can help us to discern between these effects near the middle of a burst must await future observations.

With this assessment, we conclude that a  $\sim 12 r_g$  hot, magnetized Keplerian flow can account for the temporal behavior of the X-ray flare quite naturally. Adopting quasi-steady conditions in the accretion model for Sgr A\* (Melia et al 2001), we note that the structure of the disk is then determined primarily by  $\dot{M}$  and the anomalous viscosity through this region. The inner boundary condition is chosen such that the stress is zero there. At the outer boundary  $r_o$ , we also need to know the gas temperature  $T_o$ . But this is not difficult to constrain in cases where the inflowing gas is emitting inefficiently before it circularizes (which appears to be the case for Sgr A\*); we would expect that  $T_o$  should be close to its virial value at that radius, i.e.,  $T_o \sim 2GM m_p/9kr$ , where  $m_p$  is the proton mass and  $k$  is the Boltzmann constant.

Figure 1 shows the profiles of temperature and density as functions of radius for the inner

$\sim 12 r_g$  of the Keplerian region in the quiescent state, based on the hot, magnetized disk model described above. The spectral fit corresponding to these conditions is represented by the thin solid curve in Figure 2 (see also Liu & Melia 2001). For this, and all other, models discussed in this paper, the Keplerian structure has an inclination angle of  $45^\circ$  to the line of sight, an inner boundary  $r_i$  of  $2.4 r_g$  (we use Newtonian geometry for these calculations—the full relativistic treatment will be incorporated into the more detailed numerical simulations to follow) and an outer boundary of  $12 r_g$ . The outer boundary temperature is set equal to 45 percent of its virial value. The best fit model for the quiescent emission has an accretion rate of  $7 \times 10^{16} \text{ g s}^{-1}$  and a viscosity parameter  $\beta_\nu = 1.0$ . For a plasma with these characteristics, there are essentially three dominant radiation mechanisms: thermal synchrotron produces the mm to sub-mm bump; self-Comptonization of these low-energy photons accounts for the quiescent-state X-ray spectrum; finally, bremsstrahlung can be significant under some conditions. For this particular fit, the high temperature and low number density result in a thermal bremsstrahlung flux density smaller than  $10^{-10} \text{ Jy}$  at all frequencies, rendering its contribution negligibly small compared to SSC.

The success of this model in accounting for Sgr A\*’s linear polarimetric characteristics (see, e.g., Bromley et al. 2001), together with the natural association we can make between the viscous time scale and the variability of the observed flare, supports the view that the outburst could well have been produced by a transient enhancement of  $\dot{M}$  through the inner Keplerian region. According to this hot, magnetized accretion model, several important changes are expected to result from the injection of new matter into the system. First, the increase in  $\dot{M}$  will increase the particle number density in the flow, which implies more efficient cooling and thus a lower temperature. The scale height of the plasma will decrease accordingly, which makes the number density even bigger. Consequently, the radio emission will become optically thin at a higher frequency. (Note, however, that an enhanced accretion rate may also affect the inner boundary condition, which we ignore in this first pass through the problem. If an additional detailed exploration of this picture is warranted by future observations of Sgr A\*, this effect will be included, along with an incorporation of the general relativistic corrections.) Second, the anomalous viscosity is also expected to change, though it is not yet understood whether  $\beta_p$  and

$\beta_\nu$  will increase or decrease. In this paper, we therefore consider both circumstances to bracket the range of possible outcomes. For example, Figure 1 shows what happens if  $\dot{M}$  is increased, corresponding to two rather diverse responses of the anomalous viscosity. The dotted curves represent the physical variables when the viscosity parameter  $\beta_\nu$  decreases by a factor of about two to 0.481. All the other parameters are the same as in the quiescent state. The decrease in the anomalous viscosity increases the number density even further, and the inflowing gas cools down to about  $10^9$  K at small radii. The decrease in  $n_B$  as the gas approaches the inner boundary is due to the zero stress condition there. The dashed curves demonstrate the behavior of  $T$  and  $n$  when  $\beta_p$  increases by a factor of about seven compared to its value in the quiescent state. With an increase in the anomalous viscosity, the effects of an enhanced  $\dot{M}$  on  $n_C$  are mostly annulled, and the structure of the inflow is therefore similar to that of the pre-flare state.

### 3. Results and Discussion

The best fit model for an accretion-induced flare in Sgr A\* is shown in Figure 2, which also shows the quiescent-state spectrum for comparison. In this case, the enhancement in  $\dot{M}$  is coupled with an associated decrease in anomalous viscosity, the combination of which results in an increase of the particle number density by a factor of 30 at the outer boundary. The structure of the Keplerian flow consequently changes considerably (Fig. 1). All three of the emission processes contribute significantly to the overall spectrum. An associated strong sub-mm/far-IR flare is expected during the X-ray outburst. Note, however, that due to a sharp decrease in the gas temperature, the mm flux is not expected to change significantly; depending on the exact model parameters, it may even decrease slightly. It is not yet certain, though, whether this can lead to an anti-correlation between the mm and X-ray flux densities, since the emission from the circularization zone further out may also contribute to the mm spectrum (see also Melia 1992, 1994). Unfortunately, the physics of this region is not yet well understood. Future high-resolution numerical simulations of the time-dependent problem may resolve this ambiguity. For this situation, the high-energy X-ray emission is dominated by bremsstrahlung processes and



the spectrum flattens during the flare. We note, however, that SSC may still contribute some flux to the soft X-ray band. This is interesting in view of the fact that a power-law fit to the flare-state spectrum suggests less absorption than expected, implying a low column density. This excess soft X-ray emission may be due to the additional flux produced by SSC above pure bremsstrahlung up to  $\sim 4$  keV. In this paper, we have adopted a quasi-equilibrium assumption for the flare state. The flare’s actual time profile may be reproduced by solving the full time-dependent dynamical equations describing the accretion flow, taking into account the possible asymmetry and diffusion induced by the additional mass injection.

Synchrotron self-Comptonization can also produce significant X-ray emission under some circumstances, specifically, when an increase in  $\dot{M}$  is associated with an enhanced anomalous viscosity. Due to a decrease in gas temperature, however, the peak of the Compton-scattered spectrum is not expected to shift significantly toward higher frequencies compared to the quiescent state. So the X-ray spectral index should change only marginally from its value in the quiescent state. This does not appear to be consistent with what has been observed. These features are evident in Figure 3, which shows the best fit spectrum when SSC dominates the X-ray flux during the flare; the predicted X-ray spectrum is simply too soft.

This situation is quite different from that of the jet model, in which SSC is invoked as the sole mechanism for producing the X-ray flare (Markoff et al. 2001). In this alternative picture, the gas temperature is a free parameter, and is arbitrarily increased by a factor of three or four to fit the flare-state spectrum. The increase in  $T$  has the dual effect of shifting the peak of the Comptonized component by more than an order of magnitude to higher frequencies, and flattening and extending the mm spectrum. The combination of these effects makes it possible for the peak of the Comptonized emission to be shifted into the X-ray domain, thereby accounting for a flattening of the spectral index during the flare. In the accretion picture, the enhanced  $\dot{M}$  suppresses the temperature sufficiently for the Comptonized component to peak at UV energies. Aside from these differences, the jet and accretion models also differ in their predictions for the associated flare at other wavelengths. The accretion model suggests that there should be

a correlated strong sub-mm/far-IR flare, whereas the jet scenario predicts a strong IR burst. Coordinated observations at mm/sub-mm and X-ray energies and at X-ray and  $\gamma$ -ray energies are now being planned for the 2002 and 2003 observing cycles, so these differences may soon lead to a possible resolution of which picture accounts for most of Sgr A\*'s radiative emission.

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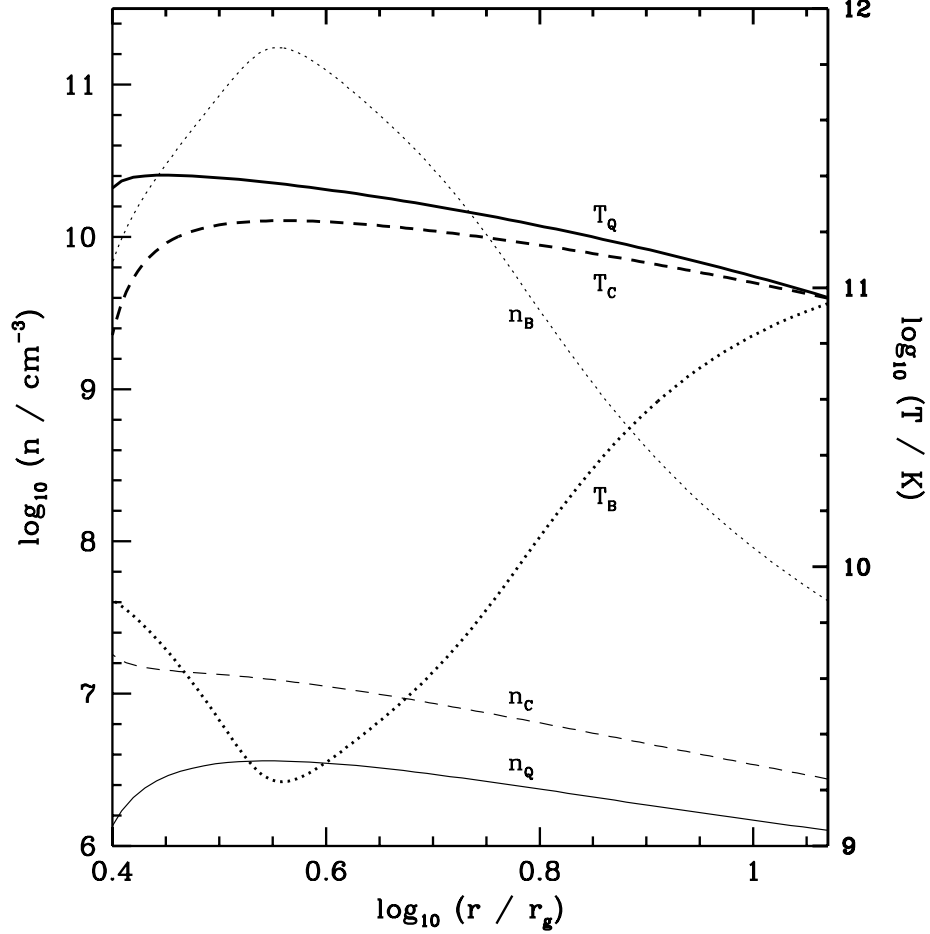


Fig. 1.— Radial profiles of the temperature (thick curves) and the number density (thin curves) of the Keplerian gas for three sets of physical parameters. In all cases, the ratio of the outer boundary temperature to its virial value is 0.45 and an inclination angle of  $45^\circ$  is assumed for the calculation of the spectrum. The solid curves show the best fit model for the quiescent state of Sgr A\* (with temperature  $T_Q$  and number density  $n_Q$ ). The accretion rate in this situation is  $7 \times 10^{16} \text{ g s}^{-1}$  and  $\beta_\nu = 1.0$ . The other parameters are  $\beta_p = 0.09$ ,  $r_o = 12r_g$ , and  $r_i = 2.4r_g$ . In Fig. 2, we will present the best fit model for the flare state, which corresponds to the dotted curves shown here (labeled  $T_B$  and  $n_B$ ). The fit shown in Fig. 3, where the X-rays are produced via synchrotron self-Comptonization, correspond to the dashed curves used here (labeled  $T_C$  and  $n_C$ ).

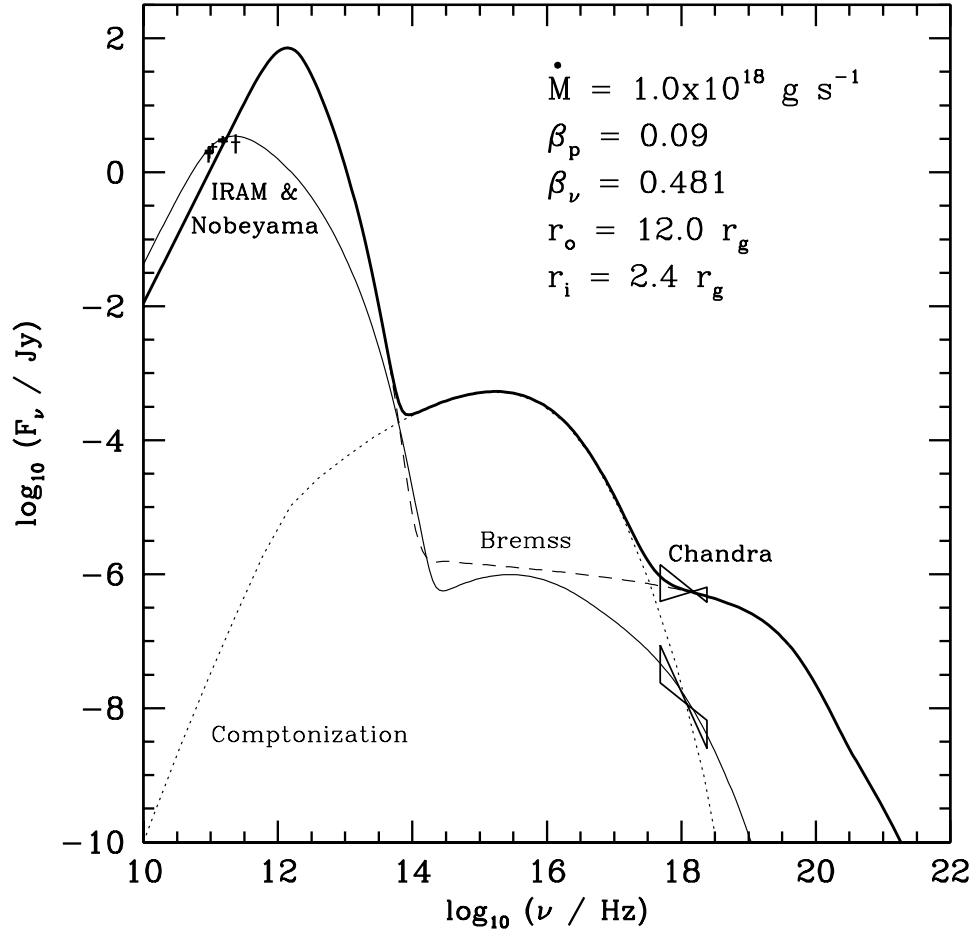


Fig. 2.— Best fit spectrum (thick solid curve) for the flare state, produced primarily with thermal bremsstrahlung emission. The physical parameters are listed in the figure. The thin solid curve corresponds to the best fit for the quiescent-state spectrum, corresponding to the dotted curves used in Fig. 1.

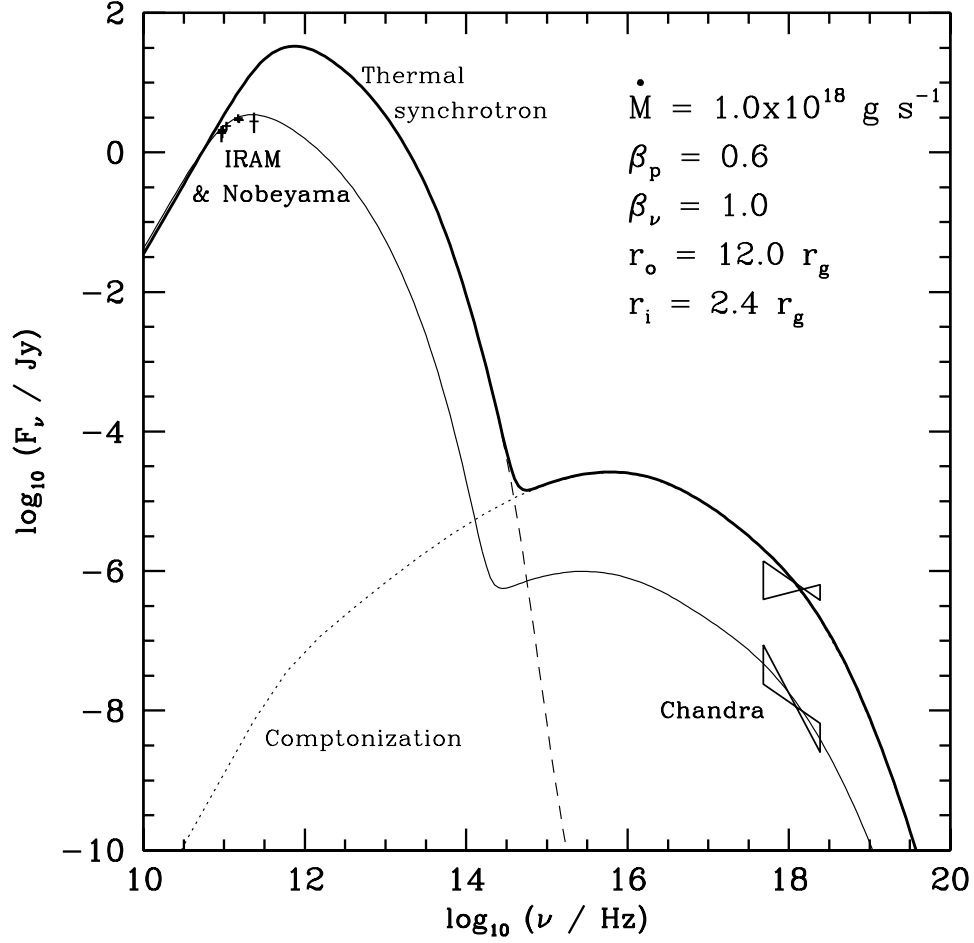


Fig. 3.— A fit to the flare-state spectrum when synchrotron self-Comptonization dominates (thick solid curve). The physical parameters are quoted in the figure. The thin solid curve corresponds to the best fit for the quiescent-state spectrum, corresponding to the dashed curves used in Fig. 1. In this case, the predicted X-ray flare spectrum is not a good match to the *Chandra* data.